Piezoelectric Actuation of Silica-On-Silicon Waveguide Devices

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***Abstract*— We demonstrate the feasibility of piezoelectric actuation of waveguide devices in silica-on-silicon. Relative to the commonly employed technique of thermal expansion by power dissipation in a resistive element, the piezo actuation drastically reduces drive-power consumption and improves switching time, from milliseconds to microseconds. We report experimental results using a discrete piezoelement, and discuss how the technique can be implemented with integrated technologies for the simultaneous fabrication of a large number of actuators on a wafer.**

***Index Terms*— Actuators, integrated optics, optical switches, piezoelectric transducers.**

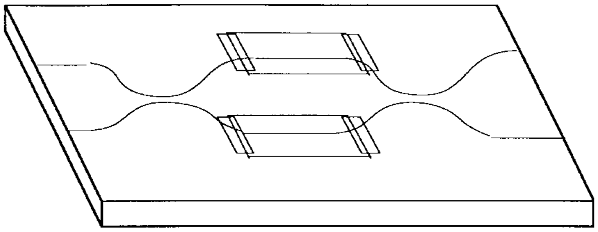

Fig. 1. A Mach–Zehnder interferometer with actuators on SOS.

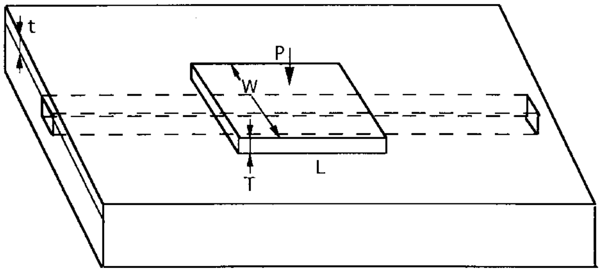

Fig. 2. Geometry of the actuator.

I. Introduction

IN NEARLY all integrated-optic devices, we find a requirement of fine trimming of waveguide pathlength or even of a large variation of the pathlength, to make the device properly work. Examples are interferometric devices like AWG's, Mach–Zehnder modulators (MZM's), but also couplers, switches, etc.

To get a pathlength actuation in homogeneous materials like silica, it is common practice to evaporate a thin resistive layer atop the waveguide to be controlled, and perform the actuation by Joule-dissipation in the resistance.

Unfortunately, thermal actuation is relatively slow, with response times in the range 0.1–1 ms, and a substantial power must be supplied in continuous-wave (CW) operation, typically 300–500 mW per element. This high dissipation hinders the use of extensive thermal control, limiting the maximum number of actuations points on a chip to a few.

In this letter, we propose a piezo technique for such an actuation and show that it is also feasible also for integrated fabrication on a chip, with an improvement of both the power dissipation (zero in CW) and the speed of response (down to microseconds).

II. Experiment

We used a silica-on-silicon Mach–Zehnder interferometer chip fabricated by Italtel, made by two 50–50 2×2 couplers with two 10-mm-long waveguides in between (Fig. 1).

Atop the guides, metal film resistors of length $L = 4.2$ mm, width $W = 25\ \mu$m, thickness $T \approx 0.25\ \mu$m (see symbols in Fig. 2) were deposited for thermal actuation. Through one pigtail of the chip, we launched about 5 mW of He–Ne power at 1530 nm, while the output ports waveforms were monitored for cross and bar powers, with two photodiodes backed by transimpedence amplifiers. Applying a step voltage to the resistor, we measured the switch power as 420 mW, and the switching time (10%–90%) as $T_r = 0.7$ ms.

To test the piezo actuation, a parallelepiped block of $L = 7$ mm, $W = 1$ mm, $t = 2$ mm was cut out from a commercial PZT slab (PIC-151 from Physik Instrument) and glued onto the waveguide with a high-stress resistant (34 MPa) epoxy cement. The piezo block was contacted on its metallization (perpendicular to W) and characterized by electrical measurements before and after glueing. Results were: a capacitance $C = 290$ pF (unvaried on glueing), a main resonant frequency $f_{\text{res}} = 90$ kHz (110 kHz before glueing) accompanied by several spurious resonances at $f \geq 180$ kHz, with a Q-factor dropping from $\approx$15 to 2.0 after glueing, as expected because of the mechanical load.

The half-wave voltage was measured in dc and turned out to be $V_{\lambda/2} = 3200$ V, see Fig. 3. As the cross and bar channels were unequal in amplitude and with a residual phaseshift unbalance at zero voltage, a least-square interpolation of data measured with $V = 0 \cdots \pm 2000$ V was carried out.

To measure the switching time, we used a high-voltage driver using avalanche transistors in a Marx-circuit configuration, supplying step voltage waveforms up to a 1500-V peak

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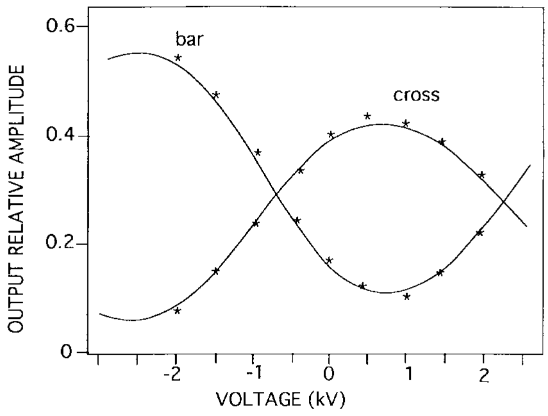

Fig. 3. Cross and bar signals out of the interferometer as a function of dc voltage applied to the piezo.

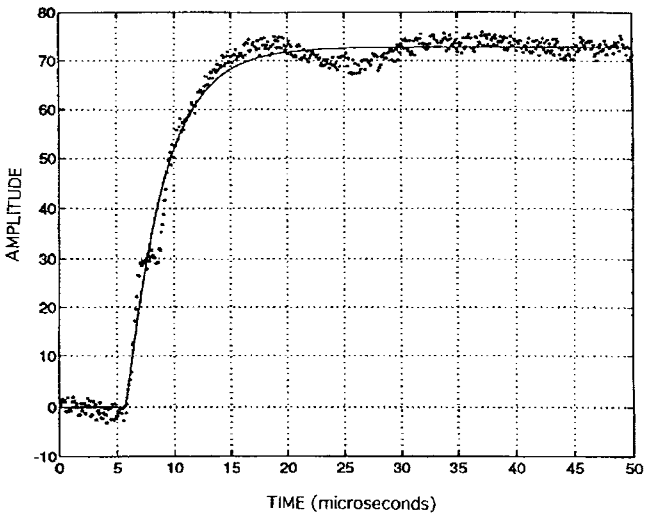

Fig. 4. Switching waveform out of the interferometer for fast step pulsing of the piezo.

and with a fast risetime of 100 ns. When pulsed, the piezo exhibited an underdamped response, with $\approx$1-μs period and a $\approx$5-μs damping time. To get closer to the requirement of no ringing of a practical device, we then slowed down the rise time of the pulser to $\approx$5 μs with a simple *RC* filter, as the best compromise between speed and residual ringing. The result measured on the bar channel is shown in Fig. 4 where we get a (10%–90%) risetime of $T_r = 7$ μs, with a residual 10% ripple (at $1/f_{\mathrm{res}} = 11$ μs).

Regarding polarization dependence, no noticeable difference was evident in the piezo actuation waveforms of Fig. 3 for TE and TM polarizations. Since polarized light from the He–Ne laser is launched into the 2-m SOS pigtail of nonpolarization preserving fiber, a polarization dependence if any should have shown up as an amplitude drift. Theoretically, as far as the applied stress is parallel to the propagation direction and nearly constant across the guide section, it is indeed reasonable to expect that no stress-birefringence is induced in the guide.

Though relatively high in our experiment, the drive voltage can be substantially decreased in a practical design. First, one can employ two piezos in push–pull arrangement to halve the voltage. Second, a thinner layer or a multilayer ceramic element can be used, reducing by a factor of 3–5 the required voltage. Thus, voltages down to 100–200 V should be easily reached.

III. Analysis

To compare the thermal and piezo actuations, let us refer to the geometry of Fig. 2, and consider first the thermal actuation. If P is the dissipated power, the layer temperature rises by $\Delta T_1 = K_t P$, where K_t(°C/W) is the thermal resistance from the layer body to the ambient, while the guide temperature will rise by $\Delta T_g = \eta \Delta T_1$, where η is a reduction factor depending primarily on the guide overcap thickness t. Then, the pathlength variation in the guide can be written as

$$\Delta(nL) = \zeta n L \Delta T_g = \zeta n L K_t P \eta \tag{1}$$

where $\zeta = dn/n\,dT + dL/L\,dT$ is the thermooptical coefficient of the guide ($\zeta = 8.1\cdot 10^{-6}$ °C^{-1} in silica [2]).

Writing the thermal resistance as [1]: $K_t = [\ln(4L/W)]/\pi\kappa L$, where $\kappa = 0.014$ W·cm^{-1} °C^{-1} is the thermal conductivity of silica, we get

$$\Delta(nL) = \zeta n [\ln(4L/W)/\pi\kappa] P \eta$$

and, by equating $\Delta(nL)$ to $\lambda/2$ as the switching condition for the interferometer containing the guide, we obtain for the required drive power:

$$P_{\lambda/2} = \pi\kappa\lambda/[2n\zeta \cdot \ln(4L/W)\eta]. \tag{2}$$

For our typical chip at $\lambda = 1500$ nm, with $L = 4.2$ mm, $W = 25$ μm, $\eta = 0.12$ (from thermal simulations), (2) yields $P_{\lambda/4} = 370$ mW, a value not far away from the measured one (420 mW). As seen from (2), the basic reason for such a high value is because of the small coefficient ζ in silica. Similar conclusions are drawn in [3].

The speed of modulation can be analyzed by an *RC*-lumped model of the circuit. Basically, it is the thermal time constant of the layer $\tau = K_t \cdot C_t$, where C_t is the thermal capacity of the layer to dominate the response. Since it is [1] $C_t = c_{sp}\pi W^2 L \cdot \ln(4L/W)$, where $c_{sp} = 0.24$ J·cm^{-3} °C^{-1} is the specific heat of silica, we can find the time constant as

$$\tau = (c_{sp}/\kappa)[W \cdot \ln(4L/W)]^2. \tag{3}$$

Inserting our data, this yields $\tau = 0.45$ ms, whence a risetime (10%–90% points) $T_r = 2.2\tau = 0.99$ ms in fair agreement with the experimentally measured $T_r = 0.75$ ms.

Turning now to the case of piezoelectric actuation, here the pathlength variation is

$$\Delta(nL) = p_{11} n L S_1 = p_{11} n L d_{13} E_3 \eta. \tag{4}$$

where S_1 is the applied strain, $p_{11} = dn/n\,dS + dL/L\,dS$ is the strain-optical coefficient of the guide (=0.121 in silica), and d_{13} is the piezoelectric coefficient of the PZT ceramic (nominally $d_{13} = -420\cdot 10^{-12} C/N$); the factor η again accounts for incomplete coupling of the generated stress to the waveguide. Equating (4) to $\lambda/2$ gives as a switching field required for actuation

$$E_{\lambda/2} = (\lambda/2p_{11}d_{13}nL)/\eta \tag{5}$$

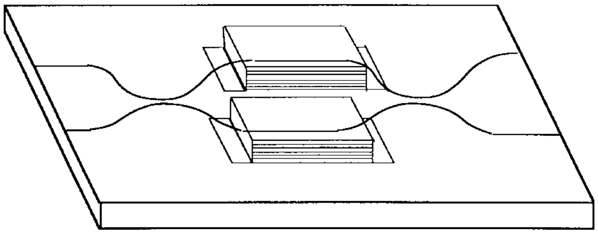

Fig. 5. Actuation by means of SMD piezo.

and this is evaluated to $E_{\lambda/2} = 1500$ V/mm for $L = 7$ mm as in our experiment, whence a value $V_{\lambda/2} = 1500$ V for the switching voltage that corresponds to $\eta = 0.44$ for our experiment.

The speed of response is determined [4] by the time spent, at the velocity of sound v_{ac} in the material (=3000 m/s), to go across the sample thickness T and establish a standing wave. Thus we have Q times the period of the resonant frequency $v_{ac}/2T$ as the minimum response time

$$\tau = 2QT/v_{ac} \tag{6}$$

that in our case ($T = 1$ mm, $Q = 2$) gives $\tau = 1.2$ μs, in accordance with measured data. Note that the product $E_{\lambda/2}\tau$ is independent from L and one can trade the half-wave voltage for speed.

Also, in the piezo actuation, no power is dissipated in dc. Only in switching, however, the electrostatic energy 1/2 CV^2 (1.4 mJ in our experiment) is dissipated, in the external circuit, at each switching (on and off).

IV. CONCLUSION

We have demonstrated that the piezo actuation can be used for the actuation in SOS integrated circuits with much better performances than thermal actuation.

To be of practical interest, however, a suitable technology of integration remains to be envisaged.

An approach readily realizable is proposed in Fig. 5: two multilayer surface-mount-device (SMD) ceramics, much alike SMD high-ε capacitors, are used in push–pull to drive the guides. The SMD's can be mounted with pick-and-place on solder pad previously deposited on the SOS with standard electronic manufacturing assembly techniques, very common in the thick-film circuit technology processes.

With data from multilayer piezo ($n = 8$ layers) of $L = 5$ mm, $W = 1$ mm, $T = 2$ mm, a drive voltage of 50 V and a switching time of 2 μs are anticipated. With such a small W, several actuators can be placed side by side for actuation in multiguide SOS optical circuits [5].

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